GUSTO Observations of the [OI] 63 µm Fine Structure Transition

Paul Goldsmith
Jet Propulsion Laboratory, California Institute of Technology

GUSTO Project Scientist

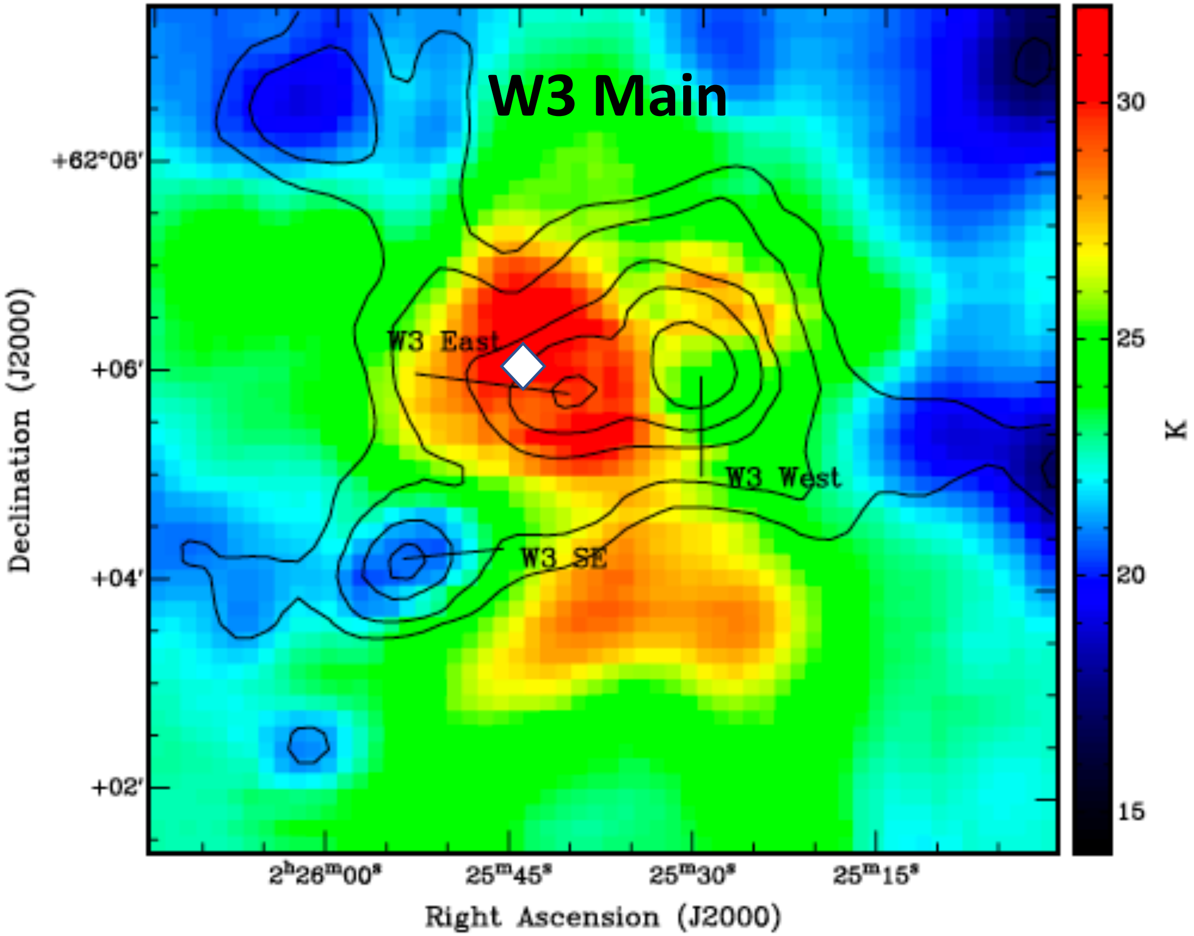
GUSTO SCIENCE TEAM MEETING
July 22, 2019

- Recent SOFIA/GREAT observations of [OI] in W3
- Prospects for observations of WNM and CNM
- Modeling [OI] emission with MOLPOP-CEP

Jet Propulsion Laboratory
California Institute of Technology

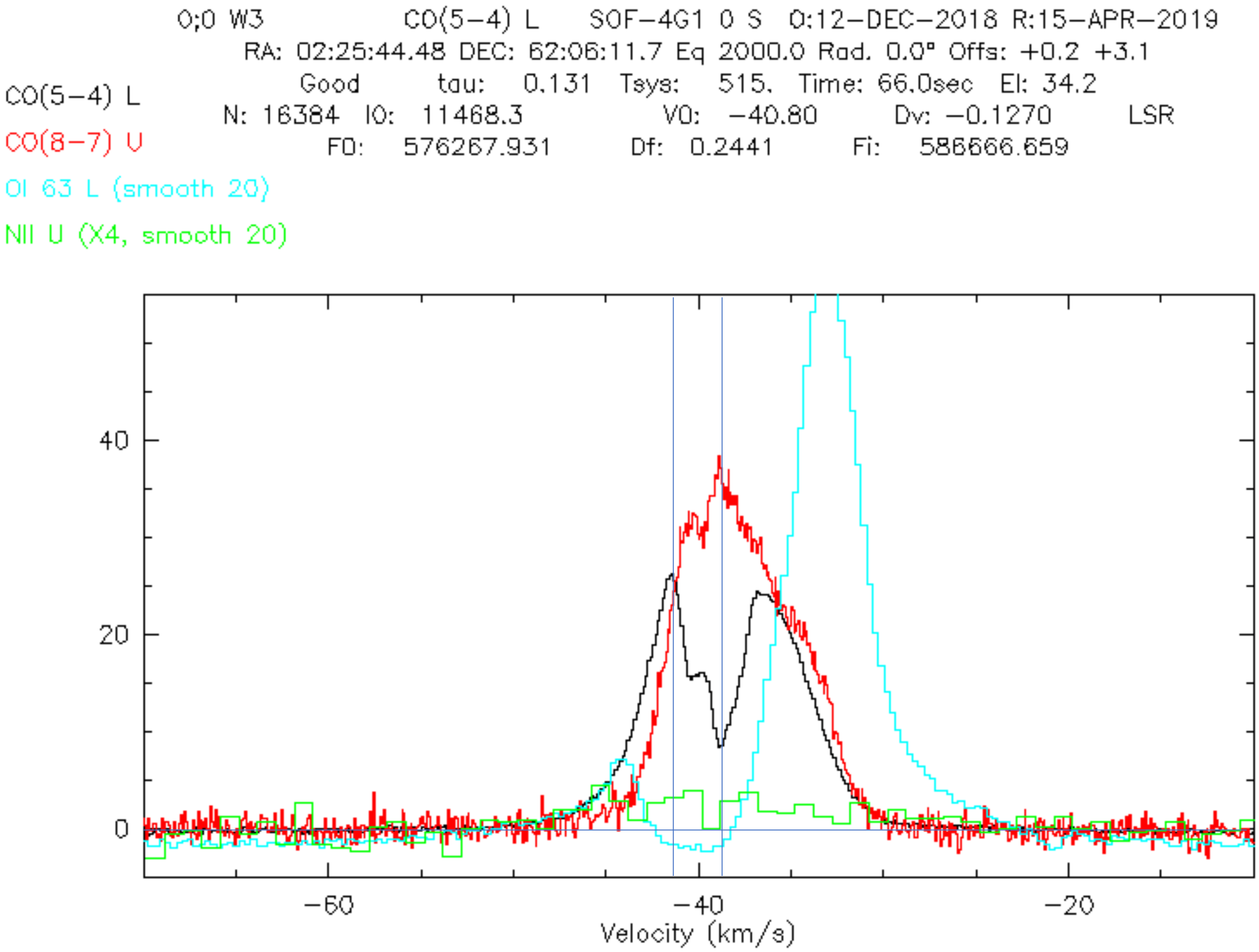
SOFIA/GREAT Observations of W3

[OI], [NII], CO 5-4, & CO 8-7

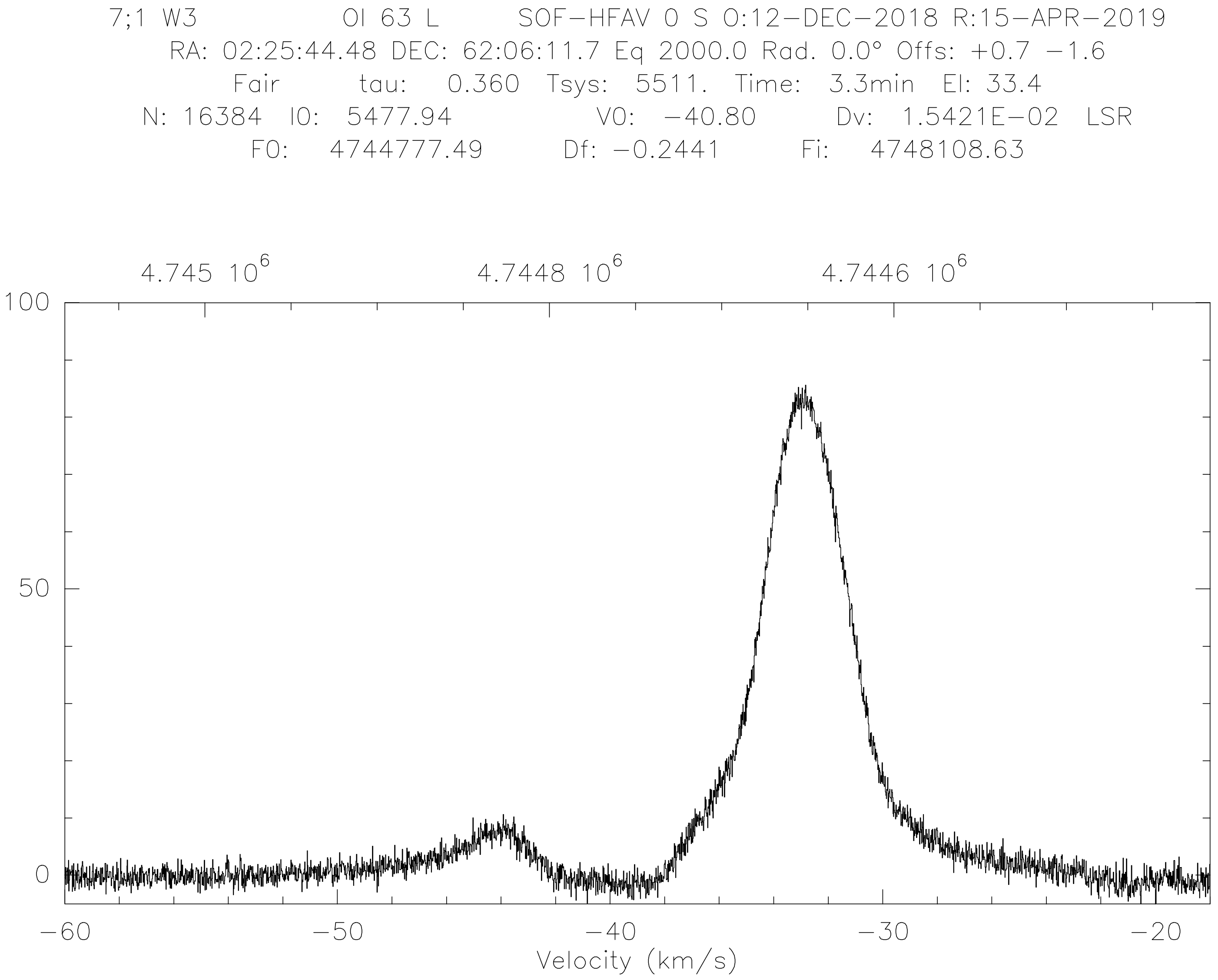


Rivera-Ingraham et al. 2013
Herschel PACS continuum observations
Contours are of $N(H_2)$

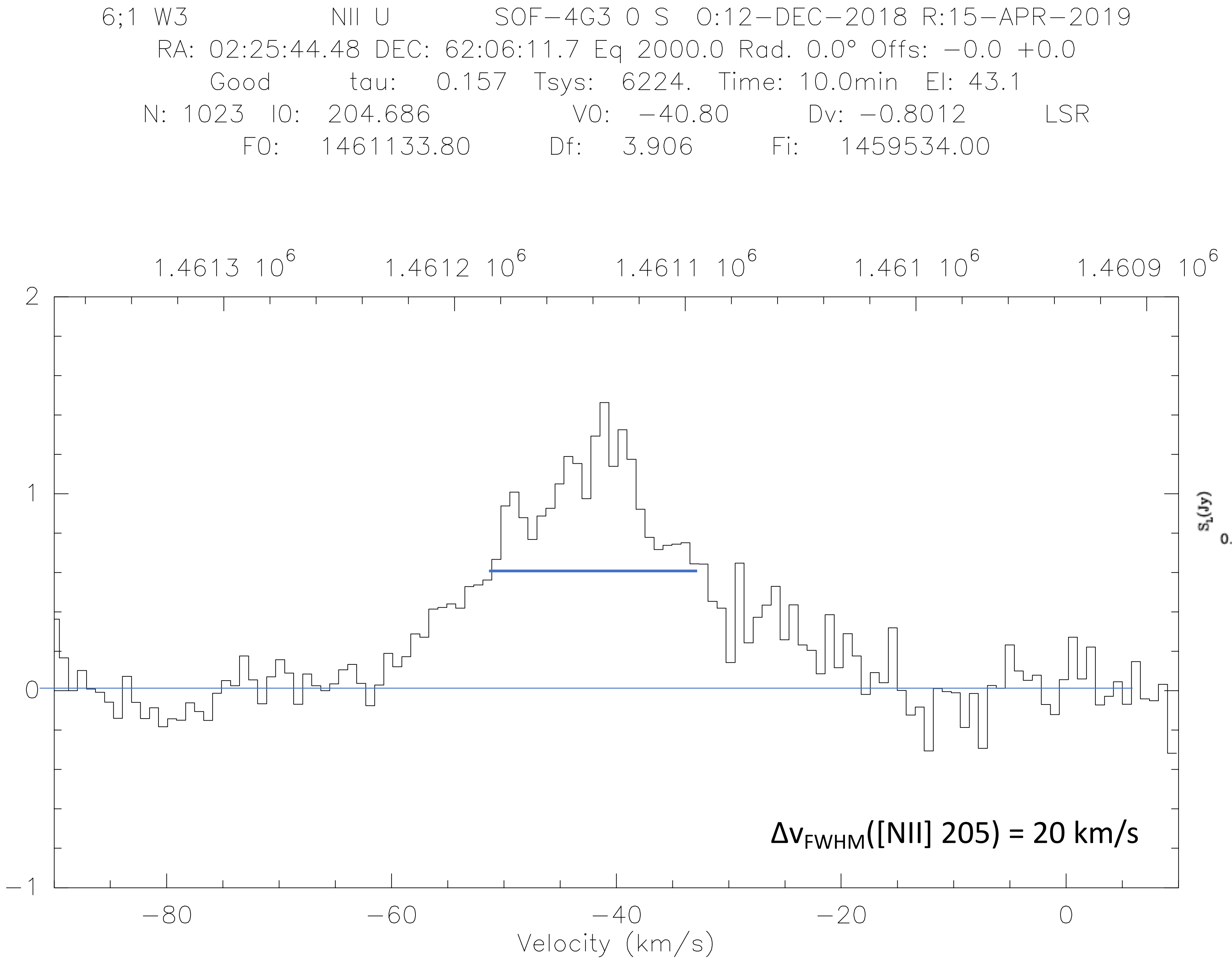
D = 2.04 kpc
M = $4x10^5$ M_{sun} (total)
M = $6x10^4$ M_{sun} (Main)
M = $8x10^2$ M_{sun} (East)
L = $1x10^5$ L_{sun} (East)
$N(H_2)$ = $1.8x10^{23}$ (East)



Δv_{FWHM}(CO 8-7) = 8 km/s

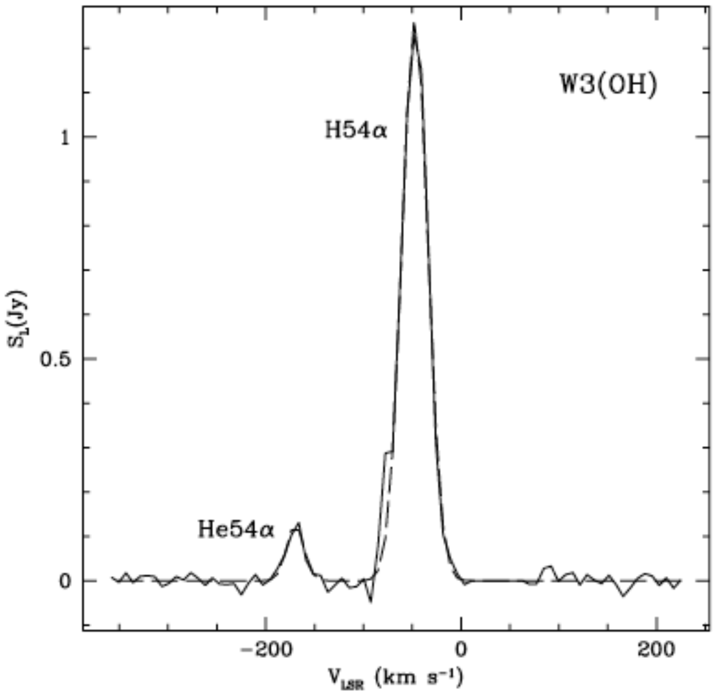

7;1 W3 OI 63 L SOF-HFAV 0 S O:12-DEC-2018 R:15-APR-2019
RA: 02:25:44.48 DEC: 62:06:11.7 Eq 2000.0 Rad. 0.0° Offs: +0.7 -1.6
Fair tau: 0.360 Tsys: 5511. Time: 3.3min El: 33.4
N: 16384 I0: 5477.94 V0: -40.80 Dv: 1.5421E-02 LSR
F0: 4744777.49 Df: -0.2441 Fi: 4748108.63
4.745 10^6
4.7448 10^6
4.7446 10^6
100
50
0
-60
-50
-40
-30
-20
Velocity (km/s)

Tmb([OI] 63) = 85 K



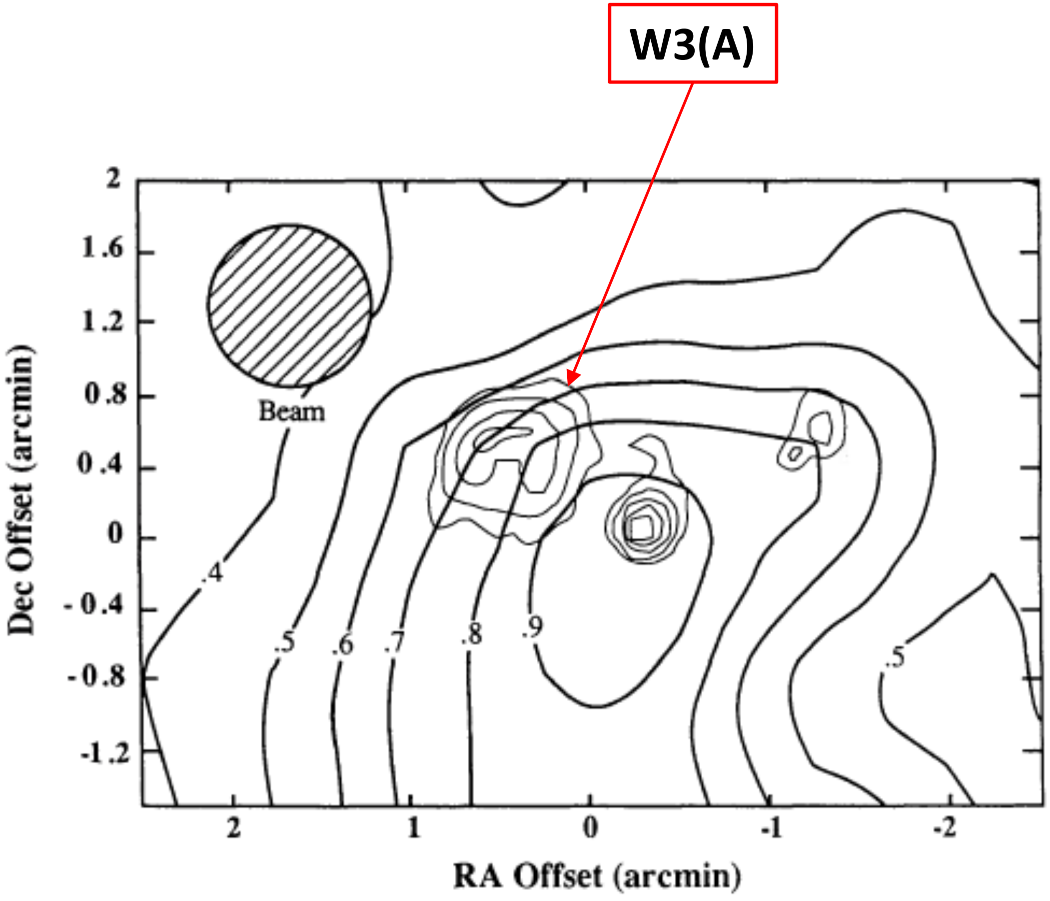
Δv_{FWHM}([NII] 205) = 20 km/s

Dzib et al. 2015



Broader than [NII]; δvthermal 10 km/s @10^4 K.

[CII] in W3



Howe et al. 1991 - KAO data

- Contours are fractions of 2.5×10^{-3} erg s^{-1} cm^{-2} sr^{-1}

- At W3 (East) I ~ 1.5×10^{-3}
- $\int T_A dv$ = 14 K km/s
- Assuming dv = 8 km/s
- $T_A \simeq 2$ K
- $T_A([NII])/T_A([CII]) \simeq 0.5$

This is a relatively LARGE value so the issue is really why [CII] is so weak!

Beamsize ~ 60” for KAO

[OI] Fine Structure Levels

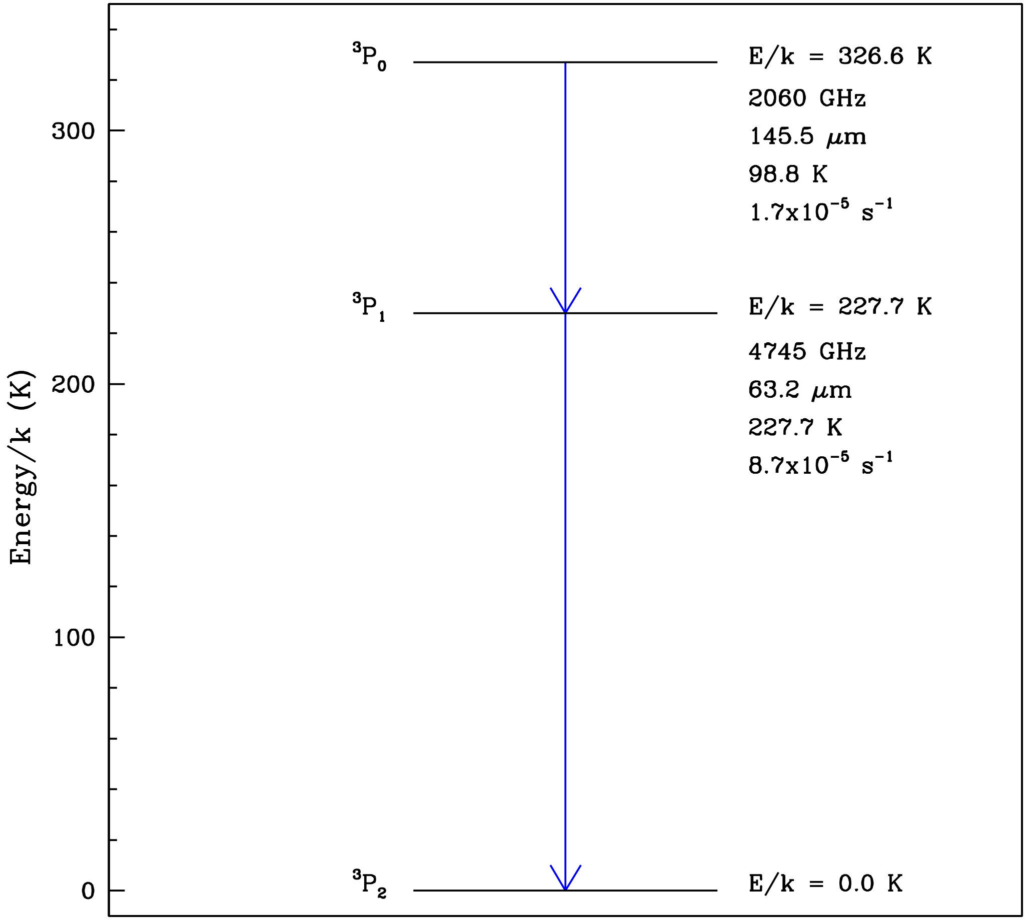


Table 1. [O I] Fine Structure Transitions and Collisional Parameters

Transition	Frequency[1] (GHz)	Wavelength (μm)	E_u/k (K)	A_{ul}[2] (s^{-1})	$R_{ul}(H)$[3] ($10^{-10}cm^3s^{-1}$)	$R_{ul}(H_2)$[3] ($10^{-10}cm^3s^{-1}$)
$^3P_0 - {^3P_1}$	2060.069	145.53	326.6	1.7×10^{-5}	0.84	.0291
$^3P_1 - {^3P_2}$	4744.777	63.18	227.7	8.7×10^{-5}	1.12	1.74
$^3P_0 - {^3P_2}$	6804.847	44.06	326.6	1.4×10^{-10}	0.76	1.36

[1] From Zink et al. (1991); these values supersede those of Saykally & Evenson (1979).

[2] From Fischer & Saha (1983). There are slight differences among different different calculations and references, cf. Baluja & Zeippen (1988).

[3] At kinetic temperature of 100 K

There is also $^3P_0$-$^3P_2$ transition but 10^4 x weaker

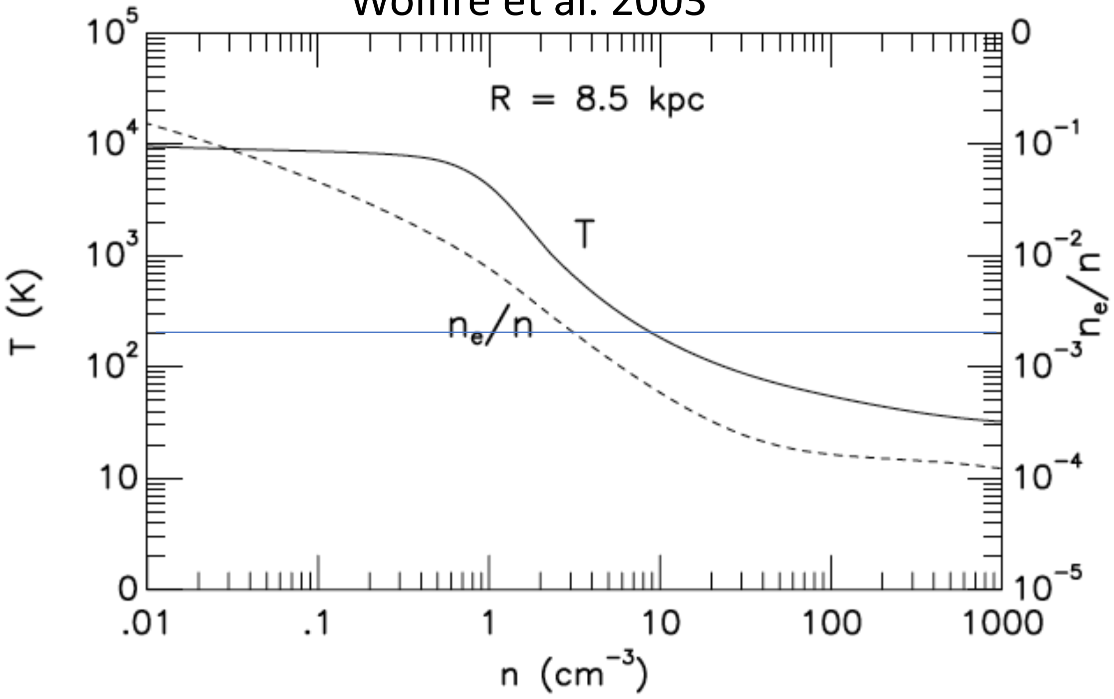
Critical Densities for [OI] Fine Structure Transitions & Excitation in Atomic ISM

based on Lique (2018) Collision Rate Coefficients

Table 4. Critical Densities for [O I] Fine Structure Transitions

Transition	$n_c(H_2)$ (cm^{-3})	$n_c(H)$ (cm^{-3})
145	5.8×10^6	2.0×10^5
63	5.0×10^5	7.8×10^5

Wolfire et al. 2003



Excitation of [OI] Lines will be extremely subthermal

Optical Depth of [OI] Fine Structure Transitions

Assume Gaussian line profile

$$\tau_0 = \frac{0.94 A_{ul} \lambda^3}{8\pi 10^5} \frac{g_u}{g_l}$$

$$\tau(\nu_0) = \tau_0 \frac{f_l N(\mathrm{cm}^{-2})}{\Delta v(\mathrm{kms}^{-1})}$$

assuming highly subthermal excitation (T_{ex} << hf/k)
f_l is the fraction of total column density, N, in lower level

Table 3. Maximum line center optical depth and lower level fractional populations for [O I] fine structure transitions

Transition	τ_0	f_l			
		T(K)			
		50	100	250	400
145	6.52×10^{-18}	6.4×10^{-3}	5.8×10^{-2}	1.9×10^{-2}	2.4×10^{-1}
63	4.92×10^{-18}	9.9×10^{-1}	9.4×10^{-1}	7.7×10^{-1}	7.0×10^{-1}

Optical Depth of [OI] 63 μm

Assume Δv = 5 km/s

$\tau = 10^{-18}$ N(O^0)

If all oxygen is O^0 :

X(O^o) = 6.6×10^{-4}

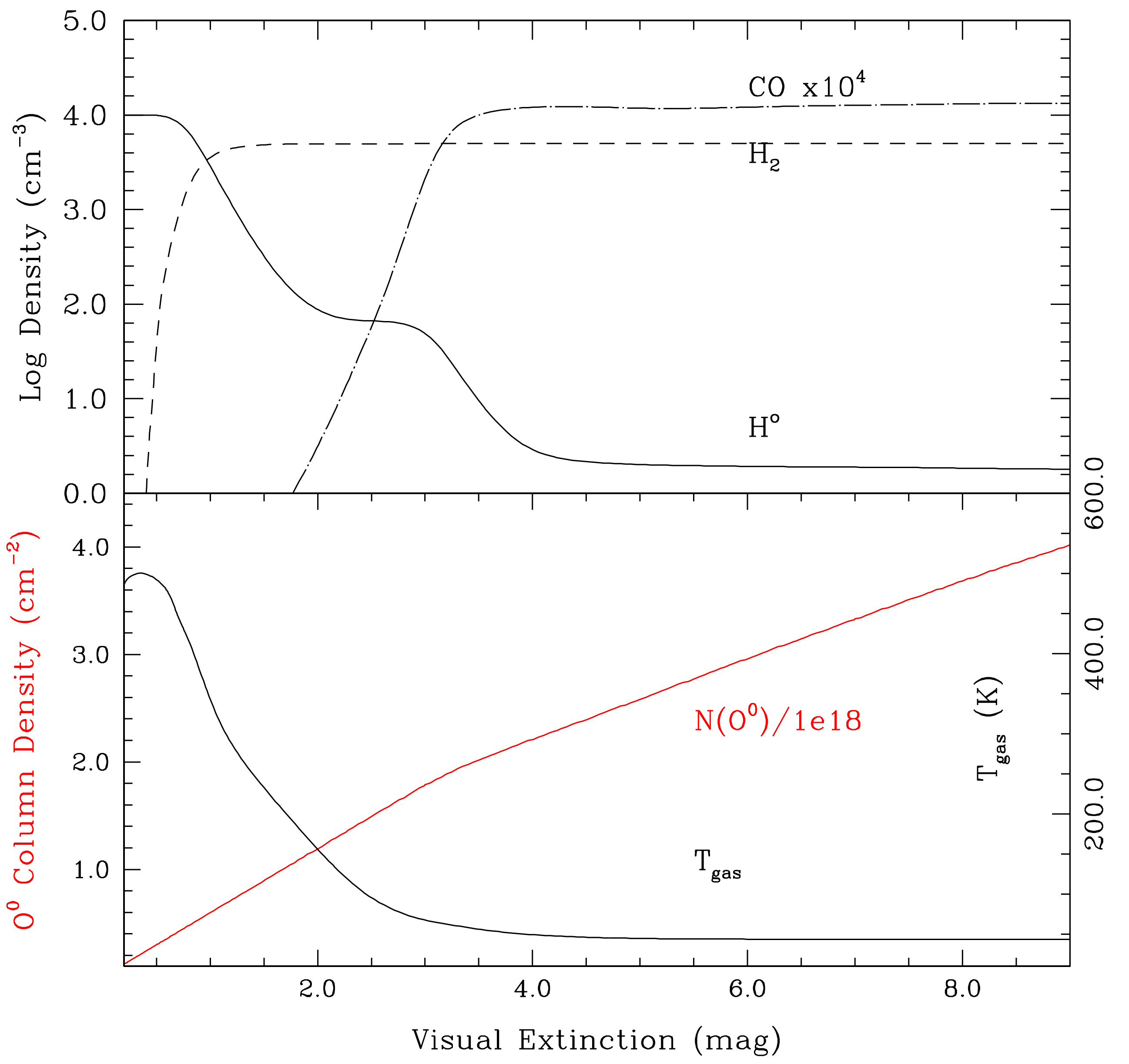
$\tau = 6.6\times10^{-18}$N(H^0)

N(H^0) = 1.5×10^{21} cm^{-2} to have τ = 1

N(O^0) increases even after oxygen primarily locked up in CO (A_V > 3)

Can get τ(63 μm) $\simeq$ 2 for large-N foreground cloud (or clouds)

τ(145 μm) << 1 due to low population at density of WNM or CNM



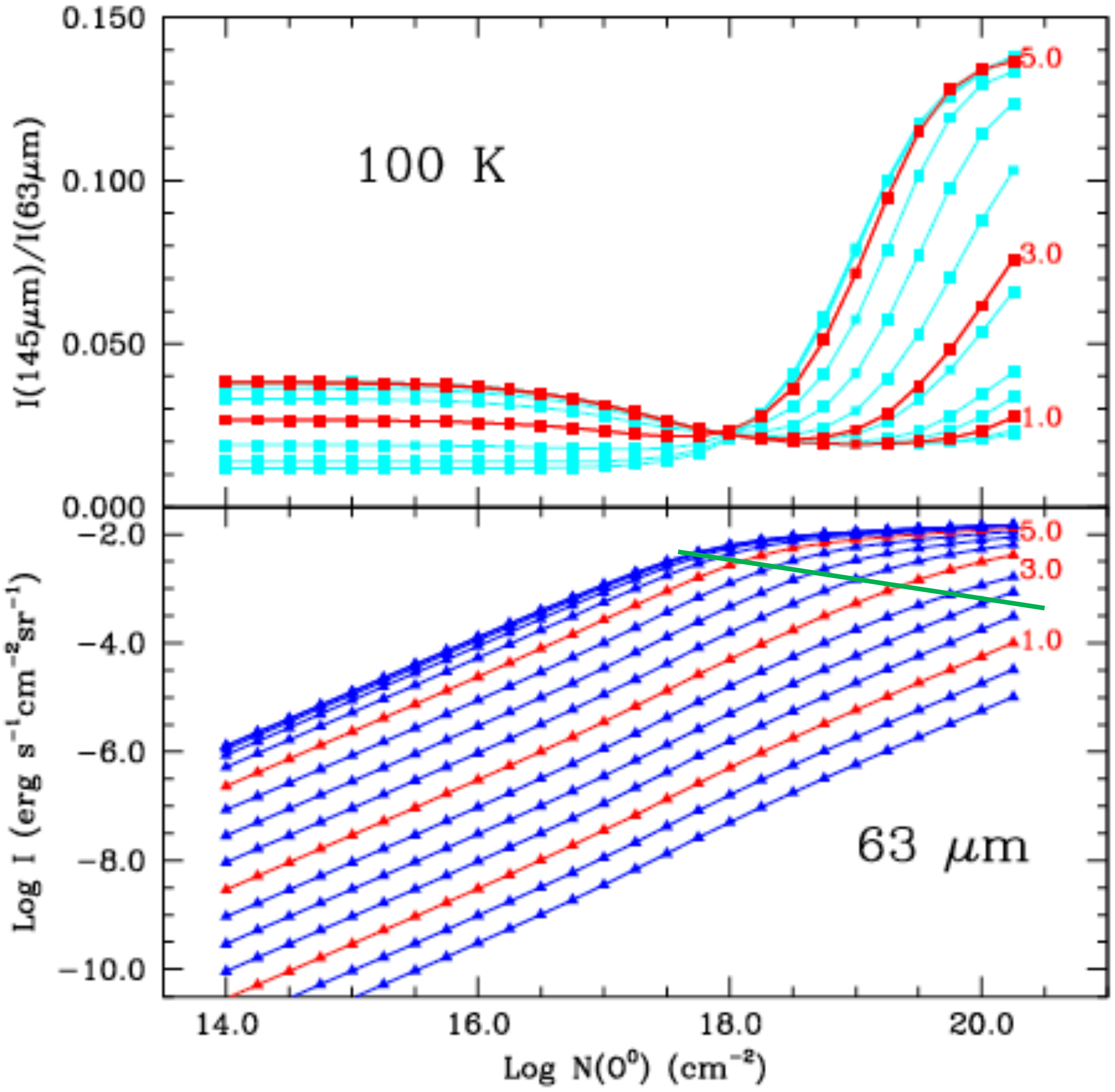


Table 2. Conversion Factors

Transition	$\Delta E/k$ (K)	T_A/I_ν (K/erg s^{-1}cm^{-2}sr^{-1}Hz^{-1})	$\int T_A dv/I$ (K km s^{-1}/erg s^{-1}cm^{-2}sr^{-1})
145	98.8	7.67×10^{11}	1.12×10^{5}
63	227.7	1.45×10^{11}	9.13×10^{3}

63 μm [OI] line is optically thick but still is "effectively optically thin" below this line

I α N(O^0)

I = 10^{-4} => $\int T_A dv$ = 1 K km/s

Notes: W43 has I_{max} = 850 K km/s
This is only for single-component emission regions ignoring all subtleties

[OI] from the WNM

$I = AN_u h\nu/4\pi$

in highly subthermal limit

$I = C_{12}N(O^0)\, h\nu/4\pi = 2.5\text{x}10^{-15}\, R_{12}\, n(H^0)N(O^0)$

Choose WNM parameters

$T = 10^4$ K, $R_{12} = 2.4\text{x}10^{-10}$ @ 10^3 K;

could be somewhat larger at 10^4 K

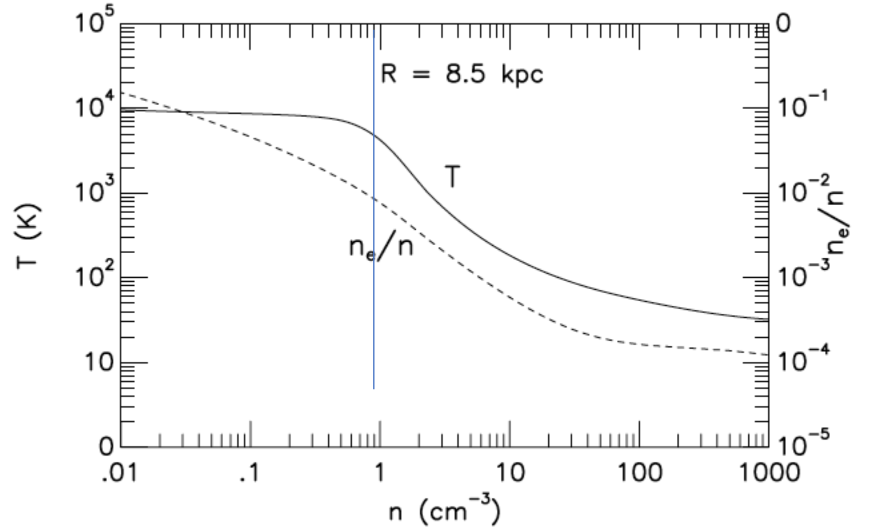
$n(H^0) = 1\ cm^{-3}$

$N(H^0) = 10^{21}\ cm^{-2}$ => $N(O^0) = 6.6\text{x}10^{17}\ cm^{-2}$

$I = 4\text{x}10^{-7}$ erg $s^{-1}\ cm^{-2}\ sr^{-1}$

$\int T_A dv = 0.0036$ K km/s

THIS WILL NOT BE DETECTABLE BY GUSTO



Wolfire et al. 2003

[OI] from the CNM

$I = AN_u h\nu/4\pi$

in highly subthermal limit

$I = C_{12}N(O^0)\, h\nu/4\pi = 2.5\text{x}10^{-15}\, R_{12}\, n(H^0)N(O^0)$

Choose CNM parameters

$T = 10^2$ K, $R_{12} = 7.2\text{x}10^{-12}n(H^0)$

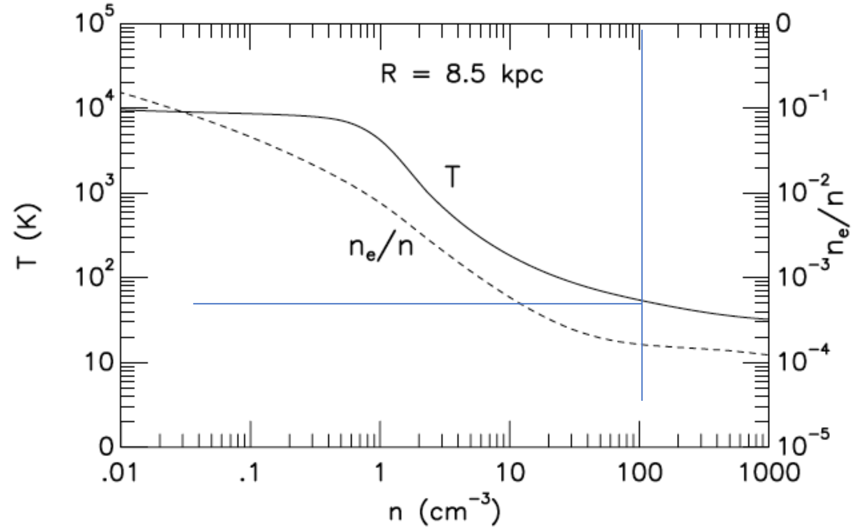
$n(H^0) = 100\ \text{cm}^{-3}$

$N(H^0) = 10^{21}\ \text{cm}^{-2} \Rightarrow N(O^0) = 6.6\text{x}10^{17}$ cm

$I = 1.2\text{x}10^{-6}$ erg s^{-1} cm^{-2} sr^{-1}

$\int T_A dv = 0.0011$ K km/s

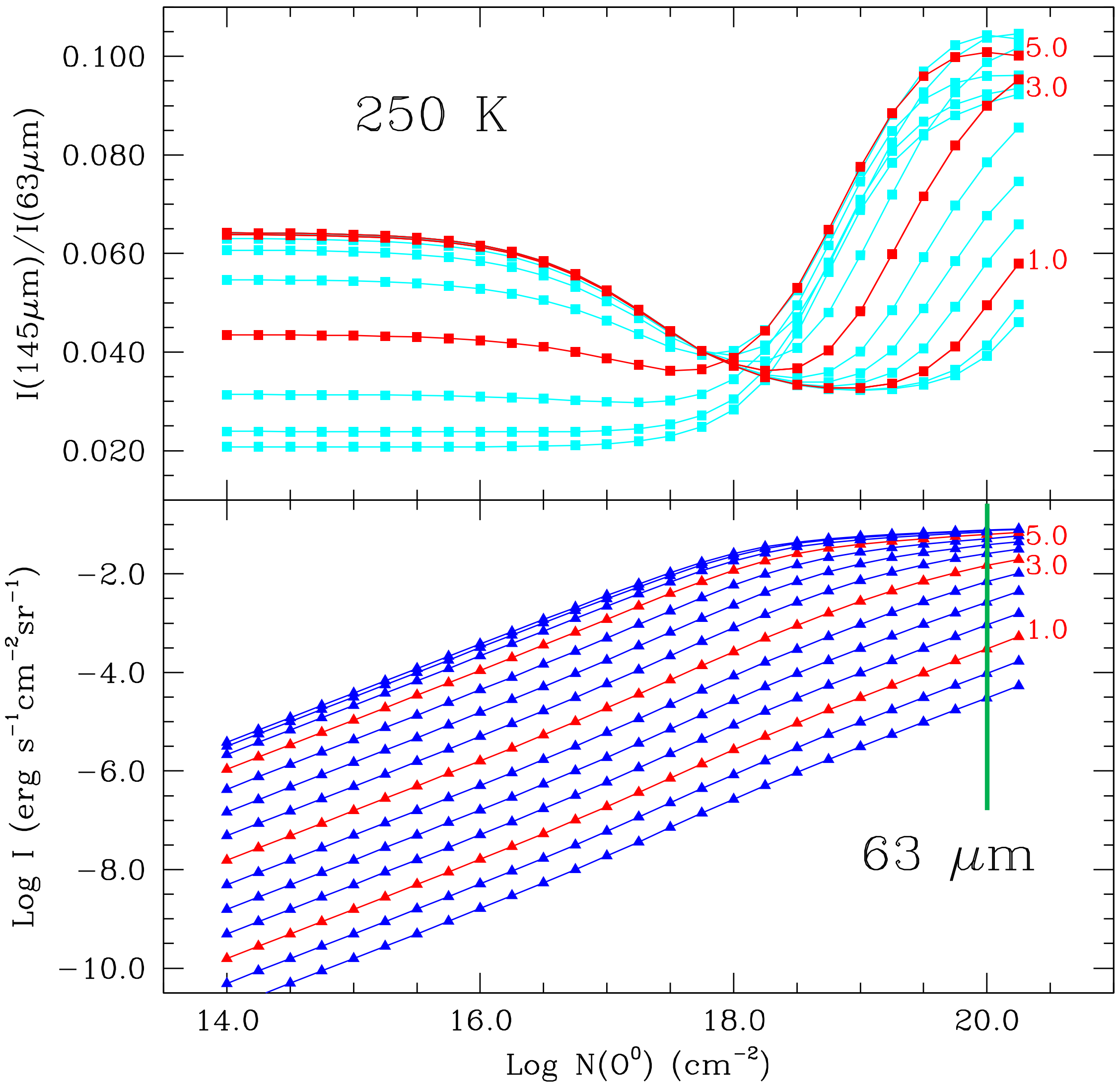
THIS WILL NOT BE DETECTABLE BY GUSTO



[OI] from PDRs

The big difference is that you have large column density of warm, dense gas in which oxygen is still in atomic form due to radiation field

$N(H_2) = 10^{23}$ cm^{-2}
$N(O^0) = 10^{20}$ cm^{-2}
T = 250 K
I = 3x10^{-2} erg s^{-1} cm^{-2} sr^{-1}
$\int T_A dv$ = 270 K km/s; with dv = 5 km/s
T_A = 55 K
This is characteristic of resolved, energetic PDRs including W3 and others that GUSTO will cover in the Galactic Plane Survey (GPS)



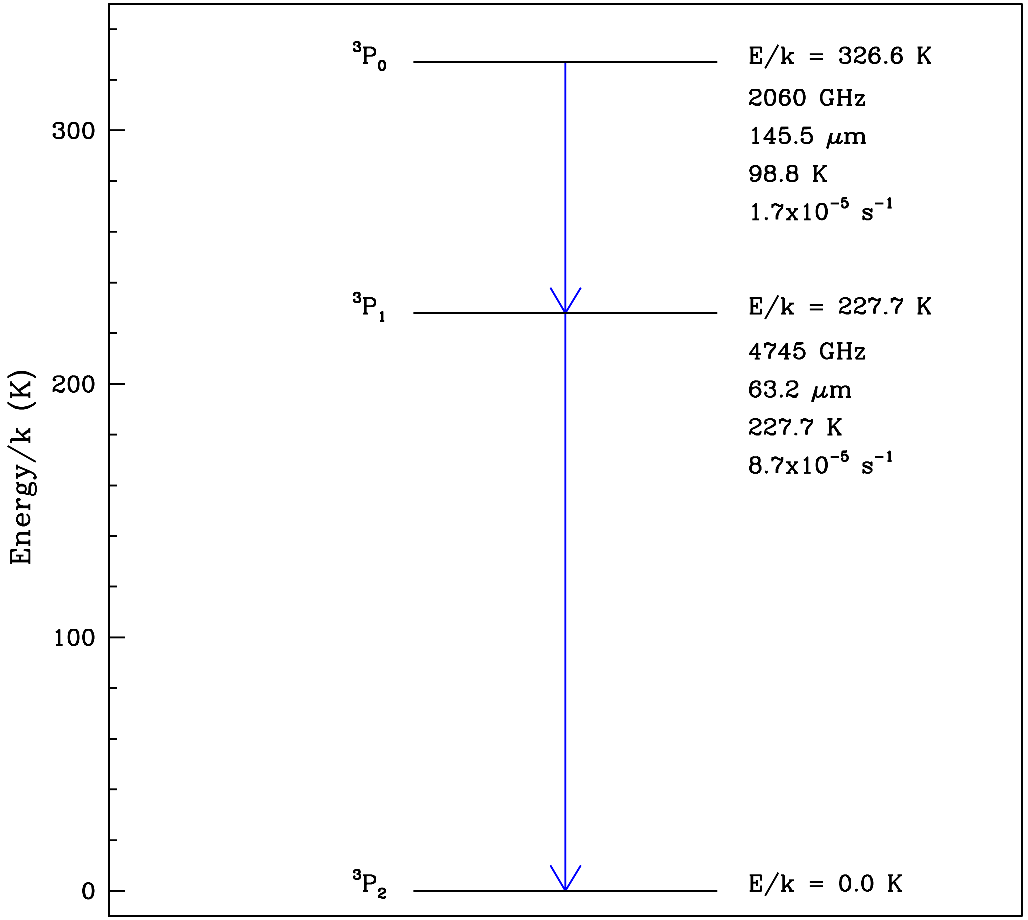
READILY OBSERVABLE WITH GUSTO

MOLPOP-CEP
An Exact Method for Line Radiative Transfer

1. Elitzur & Asension Ramos (2006)
2. Asensio Ramos & Elitzur (2018)

- Divide cloud into slabs
- Compute the escape probability for photons from each slab
- Couple photons from various slabs together
- Iterate on # of slabs to get convergence
- “CEP” = Coupled Escape Probability
- Can handle slabs with varying conditions but I will discuss only “uniform” slabs

[OI] Fine Structure Levels



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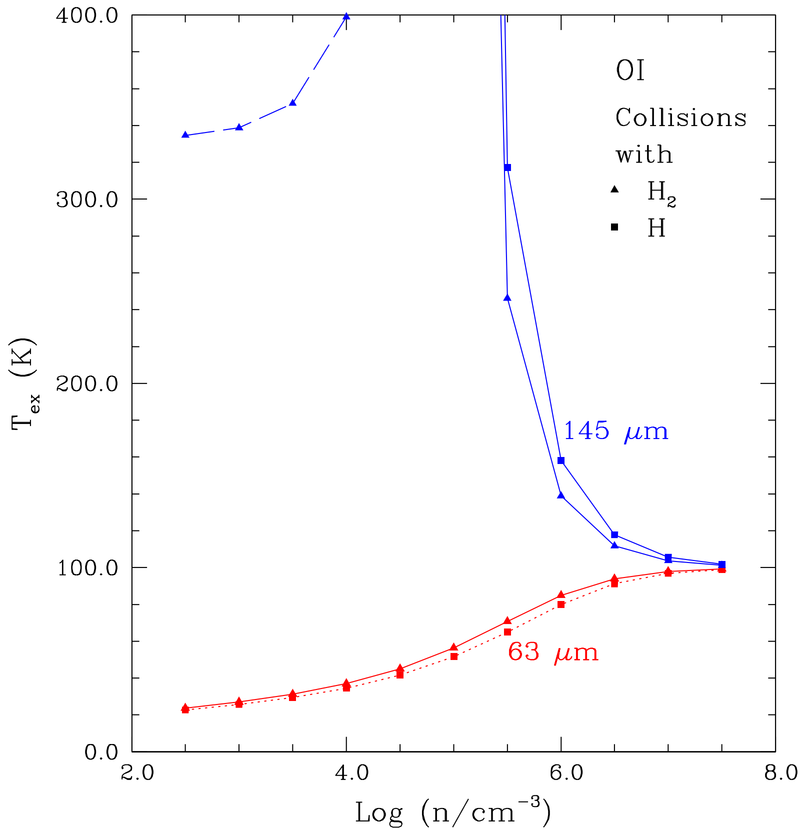
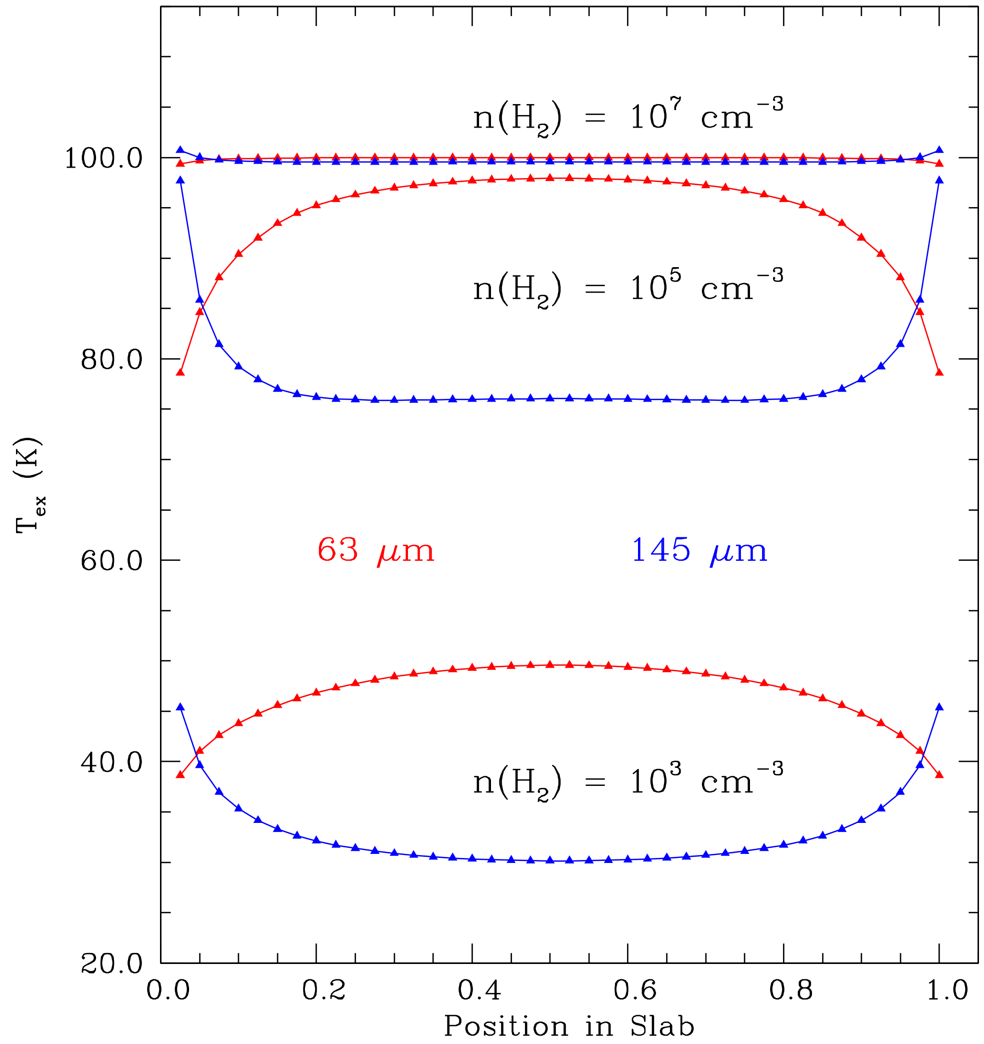


Photon Trapping Affects the Excitation Temperature when $\tau > 1$ and $n < n_{crit}$

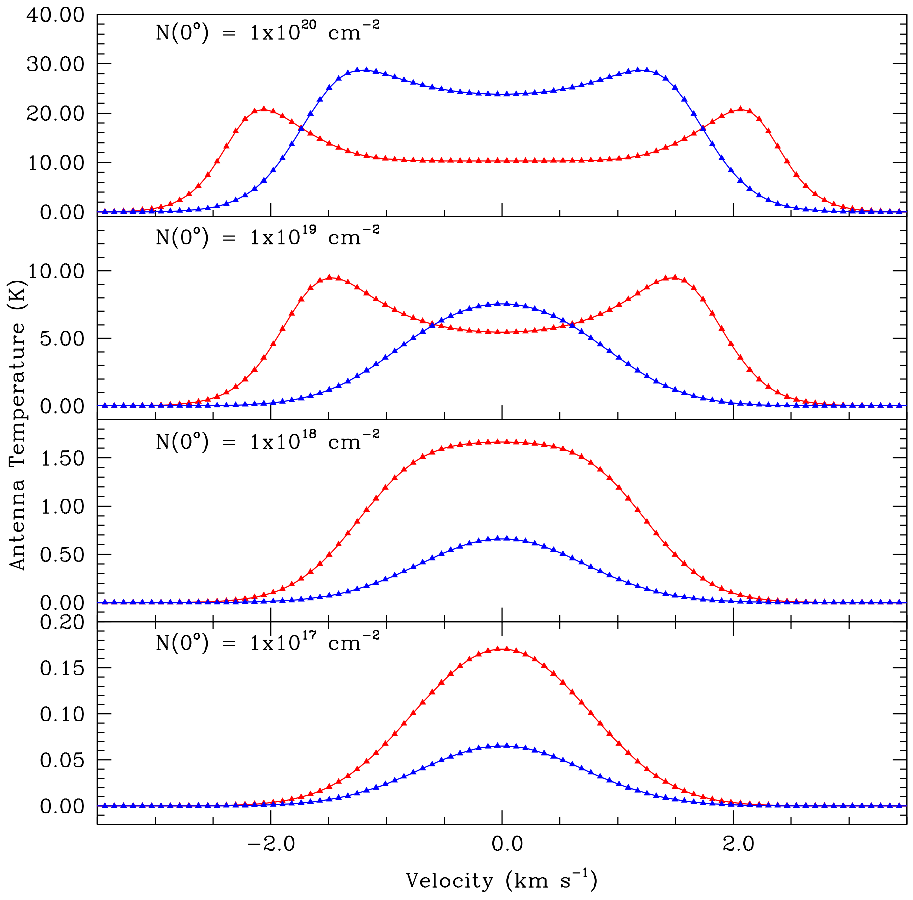


- Both transitions thermalized – T_{ex} uniform throughout slab

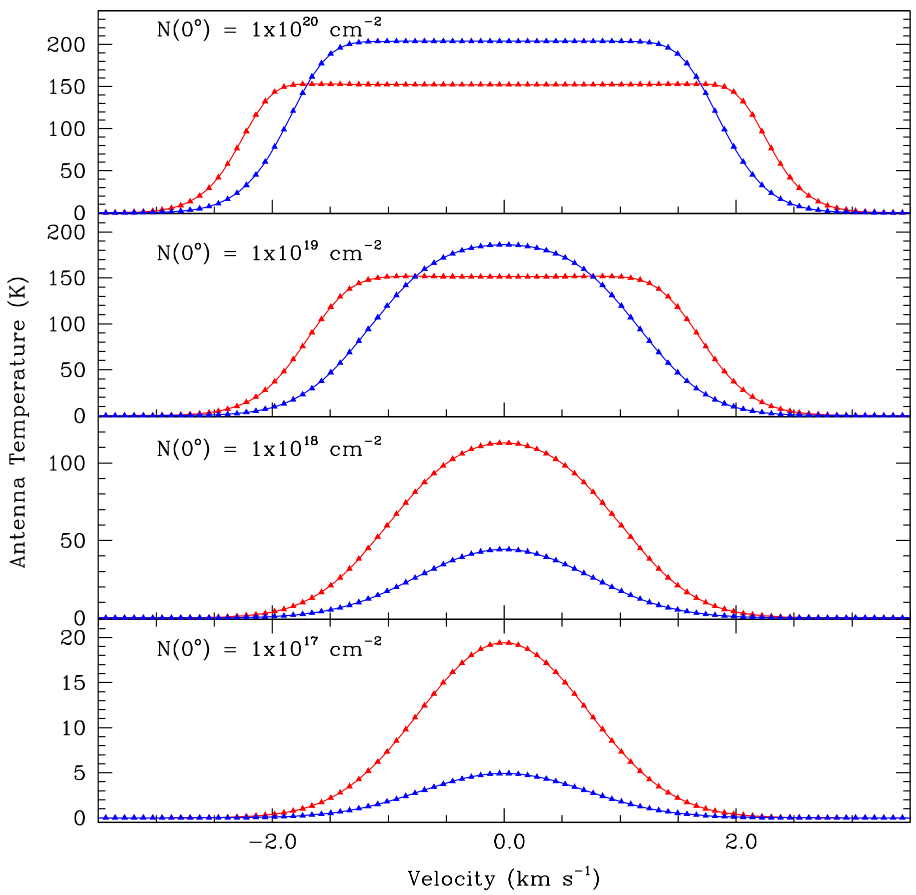
Trapping forces T_{ex} towards T_k

- 145 μm transition is superthermal so $T_{ex} \gtrsim T_k$ at cloud edges
  ⇨Tex lower in cloud center
- 63 μm transition is subthermal so $T_{ex} < T_k$ at cloud edgs
  ⇨T_{ex} higher in cloud center

Emergent Line Profiles are NOT Gaussians Although the Local Velocity Field is



T_k = 100 K
Red = 63 μm
Blue = 145 μm



$n(H_2) = 10^4\ cm^{-3}$

$n(H_2) = 10^7\ cm^{-3}$

Summary

- [OI] observations using SOFIA/GREAT confirm severe optical depth effects in 63 μm line emission from PDR regions. This has been suggested by published data.
- [OI] is likely to be unobservable from WNM and CNM with GUSTO
- [NII] emission from W3 is relatively weak
- The MOLPOP-CEP statistical equilibrium & radiative transfer program correctly handles this, allowing for more meaningful line profiles than can be produced by e.g. LVG program
- Even in “uniform” slab, line profiles show effects of self-absorption by less excited O^0 in the outer layers of the slab
- More realistic models combining physical variations as predicted by PDR models (Meudon) and MOLPOP-CEP should be a valuable tool for interpreting GUSTO data